THE LOW TEMPERATURE MICROGRAVITY PHYSICS FACILITY

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ABSTRACT

The Low Temperature Microgravity Physics Facility (LTMPF) is a state-of-the-art facility for long duration science investigations whose objectives can only be achieved in microgravity and at low temperature. LTMPF is a self-contained, reusable, cryogenic facility that will accommodate a series of low temperature experiments to be conducted on the Japanese Experiment Module Exposed Facility (JEM EF) of the International Space Station. The Facility design has been guided by enveloping the needs of a wide variety of experiments requiring highly stable thermal platforms in a dewar with a designed cryogen lifetime of approximately five months. This paper will describe the LTMPF and its goals, its design requirements, and the current status of the Facility. Opportunities for utilization and collaboration will also be discussed.

INTRODUCTION

With the era of the International Space Station (ISS) just beginning, regularly scheduled space shuttle flights for larger fundamental science payloads, such as the United States Microgravity Payload (USMP) missions, have ended. In order to continue the progress in low temperature microgravity research, highlighted by the highly successful USMP experiments, the Lambda Point Experiment (LPE) launched in 1992 [1], and the Confined Helium Experiment (CHeX) launched in 1997 [2], an alternate platform for microgravity research is needed. In 1994, the National Research Council (NRC) Space Studies Board recommended that a low temperature facility be constructed for the ISS. Later in 1995, the Low Temperature Science Steering Group (LTSSG, now the Discipline Working Group, DWG), reiterated the same recommendations. A request for proposal to build a low temperature facility for the International Space Station was distributed to the aerospace industry in 1995 and Ball Aerospace and Technologies Corporation was selected to help develop the LTMPF.

The objectives of the LTMPF are to provide more frequent access to space, to provide increased sensor capabilities thereby allowing for more diverse science opportunities, and to provide for the longer experiment operation time in the microgravity environment, as compared to the nominal two week experiment time available on the Shuttle. Much of the LTMPF concept is based upon the past experience of the two previous low temperature microgravity experiments flown on the USMP series of shuttle flights: LPE and CHeX. The LTMPF project is based at the Jet Propulsion Laboratory (JPL) and includes Principal Investigators (PIs) from around the country and co-Investigators from around the world. Home institutions of the current set of flight definition PIs include Stanford University, the University of New Mexico, the University of California at Santa Barbara, and JPL, with co-Investigators located in France and Germany. The PIs, at their home institutions, conduct ground-based fundamental low temperature physics research, define their flight experiments, and develop that part of their apparatus which is specific to their investigations. The PIs may also develop and prove new technologies necessary to perform their experiments in space. The low temperature facility includes a cryogenic dewar, electronics, mechanical and thermal support structures, and structures necessary to interface with the ISS and launch vehicles. JPL, in addition to providing overall project definition, management and implementation, will be responsible for constructing the thermo-mechanical probe structure required to interface the

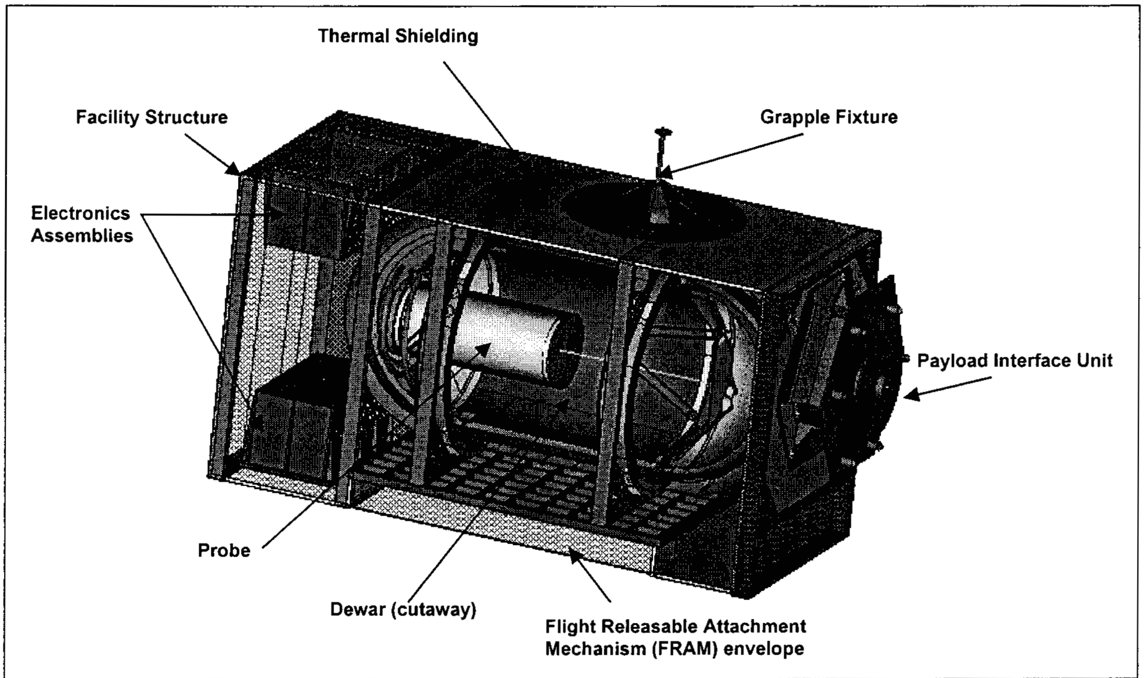

Figure 1: Conceptual Drawing of the LTMPF

experiment specific hardware to the cryogenic dewar contained in the LTMPF.

LTMPF REQUIREMENTS

In order to design a fundamental physics facility which is useful to the scientific community, input from scientists currently working in fields which may benefit from access to a low temperature environment in microgravity has been sought. A Science Requirements Envelope Document (SRED), finalized in September, 1999, was created to capture the input of the science community. Particular attention was given to the input from current flight definition PIs, who are in the process of developing their own individual science requirements specific to their experiments. The goal of the SRED is to "envelope" the needs of each of the flight definition experiments, capturing the common needs of all the experiments while at the same time insuring that PI specific items were not excluded by an evolving conceptual design for the facility. Inputs from previous flight experiments, participants of fundamental physics workshops and fundamental physics ground PIs were also incorporated into the SRED.

In addition to the requirements generated by consideration of the needs of the science community, there are many other sources of requirements which affect the design of the LTMPF. Such sources include the ISS, the Space Shuttle, the JEM EF, and the H-IIA (Japanese launch vehicle). Requirements derived from operating in space environments, such as the survivability of electrical components in space, must also be considered in the development of the facility. These requirements, as well as those derived from the SRED, are combined into a Functional Requirements Document (FRD) which guides the future design of the LTMPF.

FACILITY DESCRIPTION

The Low Temperature Microgravity Physics Facility (Figure 1) is essentially a complete low temperature laboratory that will be attached to the ISS on the Exposed Facility of the Japanese Experiment Module (named Kibo). From the LTMPF's projected carriers and docking location, the physical size of the facility is constrained to a volume of 1.85mx1.0mx0.8m and a mass of 500 kg. The current project baseline is to build two identical facilities, each of which will be capable of supporting two experiments. The key feature of each facility will be a superfluid helium dewar with the capability to reach and maintain a base temperature of at least 1.6 Kelvin for a period of approximately 5 months. This dewar will house the scientific instrument consisting of the experiment specific hardware of the PIs, integrated into a highly stable multi-stage thermo-mechanical platform.

To support the scientific instruments located inside the dewar, an extensive system of electronic and mechanical equipment, as well as thermal, electrical and magnetic shielding, and mechanical structures will be located within the facility. Electronics being designed and built for the facility will include Superconducting Quantum Interference Devices (SQUIDs) used to make precision temperature and pressure measurements, resistance thermometry and precision heaters for thermal control and experiment operation, and other electronics specific to each individual experiment. The overall design of the facility electronics will be modular and flexible to meet the needs of future experimenters. A modular system for handling gas supplies for experiment control and sample supply, as well as optical access capability to the instrument area will be available. The facility will also provide a flight computer for control of all facility and instrument electronics, as well as for command, telemetry and data storage during on-orbit operations.

Most candidate experiments are sensitive to random vibrations, charged particles, and stray magnetic fields. LTMPF will be constructed with a passive vibration isolation system attenuating vibration levels from the ISS below 500 μg rms at the instrument. Several layers of magnetic shielding will be built into the instrument probe to protect the experiments from on-orbit variations in the magnetic field environment. The vibration and radiation levels will also be monitored and real time data will be provided to experimenters. The facility will be built with the mechanical and thermal structures necessary for survival in the environments that will be encountered from launch and attachment to the ISS, through return and landing of the LTMPF on the Space Shuttle.

LIFECYCLE OF THE LTMPF

Once the facility and the two flight experiments have been built and tested by their developers, the hardware will be shipped to JPL for final integration and testing. After integration, the entire facility will be shipped to the launch site cold. The facility is manifested for its first launch on board a Japanese H-IIA rocket. Launch of the LTMPF is scheduled for June, 2004 from the Tanegashima Space Center in Japan. Subsequent launches of the facility may be by H-IIA rocket or, more likely, by the Shuttle. However, the LTMPF can only be returned by the Space Shuttle. The current baseline is to build two identical facilities, which will make it possible to integrate and test the next set of flight experiments while one of the facilities is docked on the ISS taking data. It is estimated that there will be a 1 to 2 year cycle time between flights of the facilities. Once on station, the experiments will be simultaneously taking data for approximately five months. After cryogen depletion, the LTMPF may continue to monitor environments on board the ISS while it awaits return by the Space Shuttle. On return to Earth, the experiments will be deintegrated from the facility and may then undergo some post-flight testing at the PI home institution. The facility will be refurbished for the next set of experiments and the new experiments will be integrated for the next launch. Each facility is being designed to survive five cycles of testing, launch and landing, providing for up to twenty years of service and microgravity access to low temperature, fundamental physics investigations.

FLIGHT DEFINITION EXPERIMENTS

There are currently six candidate experiments competing for flight opportunities onboard the LTMPF. A brief description of these experiments, including a description of their need for microgravity, follows. The investigations were chosen through the NASA Research Announcement (NRA) selection process. This selection process occurs on an average of once every two years and the experiments are selected through peer review based on scientific merit and need for microgravity. The experiments include the Superfluid Universality Experiment (SUE), Critical Dynamics in Microgravity (DYNAMX), the Microgravity Scaling Theory Experiment (MISTE), Boundary Effects on the Superfluid Transition (BEST), Experiments Along Coexistence Near Tricriticality (EXACT), and the Superconducting Microwave Oscillator (SUMO). Many of these experiments are condensed matter experiments performed using liquid helium samples (^{3}He and ^{4}He) and make use of high precision, SQUID-based thermometry which was originally developed for LPE. The current candidate experiments have continued this sensor development and have made improvements on the inherited techniques. SUMO represents a class of experiments exploring gravitational and relativistic physics in a low temperature microgravity environment.

SUE

John Lipa, of Stanford University, is the Principal Investigator of SUE [3]. The main science objective of SUE is to test a fundamental aspect of all phase transition theories: Universality. Universality states that certain key parameters in a system undergoing a phase transition are invariant under wide variations of other non-key parameters. The test of Universality can also help illuminate other areas of physics such as the Standard Model of matter. SUE will measure the second sound velocity, which is the velocity of temperature waves, in superfluid ^{4}He to determine the critical exponent ν (key parameter) predicted by renormalization group theory for various pressures (non-key parameter) near the lambda line. While the theoretical prediction of the exponent ν is not exact, the universality prediction, that ν be independent of pressure, is an exact prediction. The transition between superfluid and normal fluid in ^{4}He is a second order phase transition and is known as the lambda transition, or the lambda point, named for the shape of heat capacity versus temperature curve. Measurements have shown that the superfluid transition temperature is pressure dependent. On Earth, therefore, a sample of helium liquid will have a gravity induced pressure gradient, and hence a variable transition temperature along the sample height. This inhomogeneity in the sample shifts the lambda point transition temperature by approximately 1 μK per cm of fluid height. This inhomogeneity can be reduced by reducing the sample height, however, there is a competing requirement to keep the sample large to avoid finite size effects. As a result, and despite current measurement technology achieving temperature resolutions of better than a nanokelvin, the 1 μK/cm inhomogeneity in the sample on Earth makes the asymptotic region very near the transition temperature experimentally less accessible.

DYNAMX

While most critical behavior experiments address static properties at equilibrium, DYNAMX probes dynamic properties near criticality under non-equilibrium conditions [4]. Like SUE, DYNAMX is performed in ^{4}He near the lambda transition, and is limited by the gravity induced inhomogeneity in the superfluid. The experiment measures the thermal conductivity in helium in the presence of a heat flow and the measurements made will be compared to predictions of the Renormalization Group Theory. The data from DYNAMX are obtained by making temperature profile measurements with high resolution thermometry probes placed along the sidewall of the sample cell. The experiment will also improve the determination of the lambda point transition temperature under a heat flow and search for hysteresis behavior near the transition. The Principal Investigator, Robert Duncan, and his team perform their research at the University of New Mexico.

MISTE

The science objectives of MISTE, headed by Principal Investigator Martin Barmatz of JPL, are to measure critical exponents near the ^{3}He critical point in microgravity and to provide a very accurate test of the scaling law predictions of the Renormalization Group Theory [5]. The critical exponents α, γ, and δ will be determined from measurements taken in the same experimental cell. While there are uncertainties in the theoretical prediction of each exponent, they should follow exact scaling relations. Determination of the critical point parameters, the critical pressure, density and temperature, are important to the success of this experiment. Ground-based measurements of this type are limited by a strong divergence in the isothermal compressibility of ^{3}He near the liquid-gas critical point leading to a gravity induced density gradient. The gradient limits the experimentally accessible range of the asymptotic region, a region of great theoretical interest, near the critical point. The measured critical exponents from the flight experiment will be compared to the theory and used to test the scaling relations.

BEST

The goal of the BEST experiment is to provide the first test of the validity of dynamic, finite-size scaling theory [6]. It will quantitatively examine the effects of solid boundary, finite-size confinement and dimensionality on the critical thermal transport near the superfluid transition in ^{4}He and compare results to dynamic finite-size scaling theory. The experiment will measure the thermal conductivity under one dimensional and two dimensional confinement of varying sizes and compare these measurements to theoretical predictions. BEST will also improve on measurements of the thermal conductivity in a three dimensional sample along the lambda line with improved temperature resolution. The range of measurements proposed by BEST can only be achieved in a microgravity environment. The cross-over behavior from a three dimensional superfluid to a superfluid transition in two dimensions will also be examined. The Principal Investigator on BEST is Guenter Ahlers of the University of California at Santa Barbara.

EXACT

Melora Larson of JPL is the Principal Investigator for EXACT [7]. EXACT will perform a rigorous test of "exact" predictions made by Renormalization Group theory at the tricritical point of liquid helium. The science objectives of the experiment, performed in ^{3}He-^{4}He mixtures, include measuring the superfluid density exponent, ν, along the coexistence curve and measuring the shape of the coexistence curve and the lambda line as a function of temperature and concentration, thereby improving on the limitations imposed by ground measurements by up to two orders of magnitude. EXACT will use thin film bolometers to detect second sound temperature pulses and will measure and control the ^{3}He-^{4}He mixture concentration. On Earth a concentration gradient, proportional to the concentration susceptibility, will develop in the mixture. The susceptibility is strongly divergent near the critical point and induces a large inhomogeneity in the sample. The inhomogeneity may be minimized by reducing the sample size, but the reduction is limited by finite size effects. These conflicting constraints restrict measurements to regions far from the tricritical point unless they are performed in a microgravity environment.

SUMO

SUMO is a unique example of a class of experiments investigating gravitational and relativistic physics in a microgravity environment [8]. The plan is to place a pair of superconducting cavity-stabilized oscillators into orbit, that can be used for experiments in special and general relativity and as local oscillators for experiments with cold atomic clocks. The project has four goals for experiments, to be performed in collaboration with other groups. SUMO will perform a test of Local Position Invariance, an assumption embedded in Einstein's Equivalence Principle for General Relativity, by comparing the frequencies of a superconducting cavity-stabilized oscillator and a laser-cooled atom clock as they move through the gravitational fields of the earth and the sun. In addition, a performance comparison, over different time frames, and a frequency comparison, as a function of pointing direction, between atomic clocks and cavity oscillators in space will be completed. The oscillator pair will also be suitable for probing the anisotropy of the velocity of light by measuring the relative frequency shift as a function of orientation in inertial space. To perform improved relativity experiments it is necessary to subject instruments to large changes of gravitational potential. The microgravity space environment is the only way to get large changes in the gravitational potential in a relatively short time scale. In addition, for experiments involving comparisons with cold atom clocks, improved performance is expected in a microgravity environment. John Lipa, from Stanford University, is Principal Investigator for SUMO.

FACILITY STATUS

The LTMPF has recently (9/9/99) completed a successful Requirements Definition Review (RDR) for the facility. A baseline design of the facility, project implementation, and science requirements were reviewed by separate non-advocate science and engineering panels. RDRs for the first three candidate experiments (MISTE, SUE, DYNAMX) will be conducted later this year and Science Concept Reviews (SCRs) for the next three experiments (BEST, EXACT, SUMO) will be held early next year. The facility will undergo a Preliminary Design Review (PDR) early in 2000, after which final design and flight build will commence.

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